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A Generic View of Toxic Chemicals and Similar Risks

*Talbot Page**

A new type of environmental problem is emerging which differs in nature from the more familiar pollution and resource depletion problems. This type of problem, which may be called *environmental risk*,[1] has rapidly increased in importance over the last few decades and may indeed become the dominant type of environmental problem. Environmental risk problems are exemplified by: the risk of leakage and contamination in the disposal of nuclear wastes; the production of synthetic chemicals which may be toxic, carcinogenic, mutagenic, or teratogenic; the risk of ozone depletion due to fluorocarbon emissions by supersonic transports; and the danger presented by recombinant DNA of the creation and escape of a new disease against which mankind has no natural defense.

Society is vulnerable to environmental risk problems for two reasons. First, because environmental risk is not yet adequately recognized as a specific type of problem, its characteristics are not well defined. A problem inadequately defined is difficult to control. Second, the characteristics

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1. "Environmental risk" will be defined specifically in terms of nine characteristics discussed *infra*. "Risk" has several distinct meanings depending on its usage. In "environmental risk," the term draws attention to the potential adverse consequences, for which the underlying probability may be highly uncertain. In this usage one speaks of the risk of cigarette smoking, the risk of war, benefit-risk analysis, but the chance, not risk, of winning the Irish Sweepstakes. See notes 4 and 44 *infra* for alternate usages of the term "risk."

which distinguish environmental risk from traditional environmental problems make environmental risk problems less susceptible to management through existing regulatory, legal, and economic institutions.

The purposes of this Article are: (1) to define the characteristics common to environmental risk problems; (2) to distinguish environmental risk from classical pollution problems of water and air pollution; (3) to highlight factors which make environmental risk problems particularly difficult to manage; and (4) to suggest a direction in management more suited to the characteristics of environmental risk and hence more likely to be effective than the current approach.

I

THE NATURE OF ENVIRONMENTAL RISK

A. *Characteristics Common to Environmental Risk Problems*

1. *Introduction*

At the level of physical mechanism, environmental risk problems may differ strikingly one from another. One may require the expertise of an atmospheric chemist, another that of a nuclear engineer, and still another that of an oncologist. However, at a more abstract level than physical mechanism, environmental risk problems share common characteristics. This section seeks to describe these characteristics and to detail their implications for the management of environmental risk problems. The discussion begins with characteristics abstracted from the problems just mentioned—nuclear power, synthetic chemicals, ozone depletion, and recombinant DNA. The nine characteristics to be proposed will not apply with equal vigor to every environmental problem, but the specification of these characteristics will help to define the nature of these risk problems and to clarify how one problem differs from another. Toxic chemicals can be viewed, then, as an especially important subgroup of a larger class of risk problems.

Of the nine characteristics, the first four—ignorance of mechanism, modest benefits, catastrophic costs, and low probability of catastrophe—emphasize the uncertainties surrounding environmental risk decision making. These four characteristics are often the focus of cost-benefit analysis. The remaining five characteristics—internal benefits, external costs, collective risk, latency, and irreversibility of effect—bear more directly on institutional problems encountered in the management of environmental risks.

2. *Characteristics Related to Zero-Infinity Dilemma*

Ignorance of mechanism is the first characteristic of environmental risk problems. The present state of knowledge of the mechanisms by which a risk is effected is both limited and limiting. Ignorance of mechanism may be present at any number of levels of risk creation, from the generation of the hazard (*e.g.*, the release of radiation from the nuclear fuel cycle) or transmission of the hazard's effect (*e.g.*, dispersion of radiation in the ambient environment or food chain) to an organism's response to exposure, particularly health-related responses (*e.g.*, sensitivity to "hot particles" and other forms of radiation). The mechanisms of generation, transmission, and response are understood so poorly that any management of these problems is truly decision making under pervasive uncertainty.

Largely because of this ignorance of mechanism, each environmental risk problem presents a gamble concerning the effect of a particular action. To illustrate, consider a simplified case of environmental risk for which there are just two hypotheses.[2] Under one hypothesis, freon hair spray propellants do not deplete the ozone layer of the atmosphere, so there is no harmful environmental effect from their use. Under the second hypothesis, freon propellants do deplete the ozone layer, thereby producing a specific environmental effect which may be enormous but is not precisely known.

The *potential for catastrophic costs* is the second common characteristic of environmental risk. What little is known about mechanism in each case establishes that each is a gamble with high stakes. But what is not known about mechanism precludes specification of just how catastrophic and likely the costs might be. Ignorance of mechanism colors the next two characteristics as well.

The third characteristic is a *relatively modest benefit* associated with the environmental risk gamble. Although some may feel that the benefits of nuclear power and recombinant DNA are not small compared with the potential cost, there appears to be at some level a strong asymmetry between potential costs and benefits, for all four examples, and for most other environmental risks. For nuclear power there is the asymmetrical gamble of a little more shielding and a little more care in waste disposal for a little lower probability of radiation release. Similarly, for recombinant DNA there is the gamble of a little more care in experimental procedures for a little lower chance that a newly created disease will escape. The situation with spray cans and ozone depletion is more clear cut. The benefits of fluorocarbons can be directly measured in markets in terms of a cheaper and finer spray compared with the alternatives, which include pump spray. These benefits accrue regardless of the potential effects of the fluorocarbons on the ozone layer. They appear modest indeed compared with the potentially catastrophic costs which might result from ozone depletion. Correspondingly, for the potentially toxic chemical Red Dye No. 40, the benefit is the cosmetic effect the color provides in foods. Again this benefit is

2. The hypotheses are called "simple" in statistical theory because there is only one hypothesized alternative. In actual cases things are not so simple. The number and kinds of outcomes are unclear, and so is the probability associated with each potential outcome.

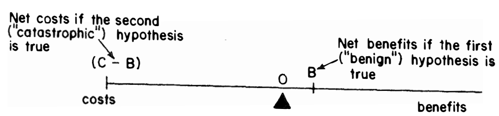
modest compared with the potential of the chemical as a carcinogen. This asymmetry in the orders of magnitude of potential costs and benefits has important implications for environmental decision making in terms of the degree of proof necessary to warrant precautionary action.[3]

An environmental risk gamble may be thought of as a seesaw with the potential costs on one side of the pivot and the potential benefits on the other. The distances from the pivot represent the relative magnitudes of benefits and costs. Figure 1 illustrates the freon propellant example. The distance from zero to B represents the benefit of the convenience of using propellants. Foregoing this convenience is the cost of opting out of the gamble. The distance from zero to C-B represents the net cost of taking the gamble and losing. The net cost is the potential, relatively large "catastrophic" cost reduced by the comparatively small benefit of using propellants that will accrue even if propellants do deplete the ozone.

In Figure 1 the potential costs, due to their greater magnitude, are considerably farther from the pivot than the modest benefits. If both hypotheses were of equal weight the seesaw would tip toward the potentially great loss. Common sense then suggests that the gamble is too risky to undertake.

Net Costs and Benefits Associated with Two Hypotheses

FIGURE I



However, there is a dilemma. There often are reasons to believe that the probabilities of the safe and catastrophic hypotheses are not equal and that the catastrophic outcome is considerably less likely than the favorable outcome. For many potentially toxic chemicals, and for nuclear power, ozone depletion, and recombinant DNA, what little is known about mechanism suggests that the probability of the catastrophic outcome is low, much lower than the probability of the favorable outcome. Just how low is impossible to say with confidence, because of the incomplete knowledge of mechanism. Due to the fragmentary knowledge of mechanism, the likelihood of the catastrophic hypothesis cannot be determined objectively, but must be assessed subjectively, based upon whatever knowledge is available.

Low subjective probability of the catastrophic outcome is the fourth characteristic of environmental risk. Common sense suggests that the low

3. See text accompanying notes 78-79 *infra*.

subjective probability of the catastrophic costs should be taken into account in balancing costs and benefits. In terms of the seesaw illustration, the probabilities of the benign and catastrophic hypotheses can be thought of as weights placed upon the seesaw at distances from the pivot equal to the magnitude of the respective potential costs and benefits. A heavy weight close to the pivot can more than balance a light weight farther from the pivot. With a low subjective probability of the catastrophic outcome and a high subjective probability of the favorable outcome, it is no longer clear which way the seesaw will tip. The fourth characteristic, low subjective probability of the potential catastrophe, introduces a second asymmetry which tends to counterbalance the asymmetry of potential high costs and modest benefits.

Whether the greater likelihood of the favorable outcome compensates for its smaller relative size is a fundamental question of environmental risk management. In the extreme case, the problem is called a "zero-infinity dilemma": a virtually zero probability of a virtually infinite catastrophe.

In the seesaw illustration, common sense may suggest that an environmental risk is worth taking as long as the seesaw, with the probability weights added, tips in the direction of the benign hypothesis. This interpretation is formally equivalent to the expected value criterion, which says that a gamble is worth taking only if the product of the benefits and their likelihood is greater than the product of the adverse outcome and its likelihood.[4] The analogy to the seesaw is used to suggest that the expected value criterion has some natural appeal as a way of balancing potential costs and benefits and their probabilities.

There are obvious limitations to the expected value criterion. It focuses on outcomes rather than processes; because of the uncertainties involved it may be difficult or even impossible to estimate the magnitudes of the outcomes or their probabilities.[5] The various uncertainties surrounding the

4. If B represents the benefits from a risky gamble and (C-B) the net costs if the catastrophic hypothesis turns out to be true, the gamble is worth taking under the expected value criterion if $p(C-B) < (1-p)B$, where p is the probability of the catastrophic hypothesis and $(1-p)$ is the probability of the benign hypothesis. In the more general case where there are several or many hypotheses and many potential outcomes, each with its probability of occurrence, the formula for expected value of the gamble is

$$\Sigma p_i q_i \quad (1)$$

where p_i is the probability of the *i*th possible outcome; if q_i is positive it is a benefit; if q_i is negative it is a cost. The expected value criterion says that the gamble is worth taking if $\Sigma p_i q_i > 0$. The analogy works because the torque of a lever (or seesaw) is determined by the same formula (1), with p_i the *i*th weight placed q_i distance from the pivot (q_i is negative if it is to the left of the pivot). The torque is clockwise if $\Sigma p_i q_i > 0$. In the example of Figure 2, $p_1 = p$, $q_1 = C - B$, $p_2 = (1-p)$, and $q_2 = B$.

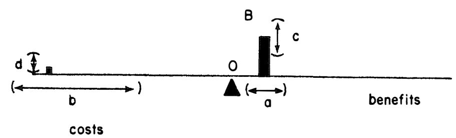
In a second distinct usage, risk is sometimes defined to mean expected value, as in (1). To avoid confusion this usage of risk will be avoided. See, in addition, note 44 *infra*.

5. The expected value criterion also does not help resolve questions of equity, irreversibility, and social risk aversion. These qualifications to the expected value criterion are discussed at text accompanying notes 80-84 *infra*.

quantification of costs, benefits, and probabilities are illustrated in Figure 2. The range of uncertainty associated with benefits, represented by *a*, is the uncertainty of *efficacy*. In the freon propellant example, it is not clear how well freon works as a propellant. The corresponding range of uncertainty associated with *costs*, represented by *b*, is typically much larger than the uncertainty of efficacy. In addition, there is uncertainty as to the *likelihood* of each hypothesis (*c* and *d*).

Costs and Benefits Weighted by Probability

FIGURE 2



The uncertainties surrounding the potential costs, benefits, and probabilities often are so strong that the decision maker avoids numerical quantification altogether. Even so, the magnitudes of the costs, benefits, and probabilities are essential considerations in environmental risk decision making, and informal estimations of costs, benefits, and probabilities cannot be avoided. Moreover, a decision to forego a final verdict on a chemical's use and to allow, or prevent, its use pending the collection of more information, is still a decision made under uncertainty.

3. *Characteristics Related to Institutional Management of Environmental Risk*

The five remaining characteristics common to environmental risk problems bear more directly on the institutional problems encountered in their management. The first of these is the *internal transfer of benefits* associated with these risks. In the case of freon propellants, the benefits—added convenience and possibly lower manufacturing costs—are transferred through markets and reflected in product prices. The economic term for costs and benefits which are thus transferred is "internal."

In contrast to an internal transfer, the adverse effects of environmental risk gambles usually are transferred directly through the environment rather than through the market. A direct, non-market transfer of an effect is called an economic externality.[6] The *external transfer of costs* is the sixth characteristic of environmental risk.[7] The failure of markets to internalize these potentially catastrophic costs is the primary reason for regulation of environmental risk problems.

6. *See* T. PAGE, ECONOMICS OF INVOLUNTARY TRANSFERS: A UNIFIED APPROACH TO POLLUTION AND CONGESTION 40-81 (1973).

The asymmetry between internal benefits and external costs, added to the asymmetry of the potential magnitudes of costs and benefits ("zero-infinity dilemma"), increases the strain on institutional management of environmental risk. The market failure associated with environmental risk is likely to be more severe than if both benefits and potential costs were external and offsetting, with the same group receiving the benefits also bearing the risks.

The seventh characteristic of environmental risk, *collective risk*, is also related to the environmental transfer of effect.[8] A risk is collective when it is borne by many people simultaneously. Since environmental transfer often means a diffusion of effect, major environmental risk problems have the potential to affect millions of people at the same time. The effectiveness of insurance, liability law, and other traditional compensatory mechanisms in protecting against loss resulting from risk is limited in the case of collective risk. The larger the potential loss and the more widespread its effects, the more difficult it is to insure.[9] Society is more averse to collective risks than to individual risks,[10] which often are managed through insurance markets.

The eighth characteristic of environmental risk is *latency*, the extended delay between the initiation of a hazard, or exposure to it, and the manifestation of its effect. For many carcinogens, the latency is from 20 to 30 years. Indeed, the mutagenic effect of a chemical may not show up for several generations. As a result of latency, those bearing environmental risks may not be the ones enjoying the benefits of the decision. Moreover, in most cases, latency is sufficiently long and the risk sufficiently diffuse so that the risk is borne involuntarily, if not unknowingly. Since an acute, or short-term, effect usually is much easier to discover and trace than a chronic, or long-term effect, long latencies increase the likelihood that the potential effects of environmental risks will be masked by other factors.

7. Environmental transfer does not imply an externality and an externality does not imply an environmental transfer. Noise in a machine shop is environmentally transferred to the workers' ears; however, if the workers bargain for higher wages in return for accepting the noise, it is also a market-compensated transfer and hence not an externality. (How well such markets work in practice is an important question, as is discussed at text accompanying note 12 *infra*.). Conversely, not all externalities involve transfer through an environmental medium; bequests and theft are external but not environmental in transfer.

8. Not all potential environmental transfers are collective risks. Lightning strikes one or few at a time and is hardly a collective risk. Conversely, a risk may be collectively borne without being environmentally transferred. While many examples of collective risk are also examples of environmental transfer of effect (*e.g.*, floods, nuclear war, ozone depletion), some are not (*e.g.*, the potential of a recession with its collective risk of mass unemployment).

9. A prime example is the unwillingness of private insurance companies to insure against losses from nuclear power plant disasters.

10. See text accompanying note 82 *infra* for further discussion.

The ninth characteristic of environmental risk is *irreversibility*. Even when an effect is theoretically reversible, as a practical matter there are important elements of irreversibility when reversal of the effect inescapably requires a long time, especially when reversal entails a high cost in addition to a long time. Irreversibility can be essentially absolute, as is the case with plutonium's half-life of 24,000 years. It can also be measured on a scale of tens of generations, as is the case with mutagens. In the freon propellant example, the stratospheric effects of ozone depletion might last a hundred years after fluorocarbon emissions are stopped. Within this essentially irreversible period of stratospheric change, however, the resulting climate modification could produce further irreversible effects, such as species extinction.

The last two characteristics, latency and irreversibility of effect, have profound ethical and institutional implications. They raise questions concerning fair distributions of risk over time and how institutions can be designed to anticipate adverse effects, rather than merely to react to existing, known effects.[11]

4. A Typology of Related Problems

Environmental risk can now be defined as the class of problems having the foregoing nine characteristics. These characteristics are shown schematically in Figure 3 (on page 217). A typology of related problems subject to analysis based on these nine characteristics is presented in Table 1. This table facilitates use of the nine characteristics to determine whether, and to what extent, a particular problem is of the environmental risk type.

An "X" in the column underneath a particular characteristic indicates that it occurs in the corresponding problem. A typical environmental risk problem, as illustrated by the first example in Table 1 (ozone depletion due to use of freon propellants), exhibits all nine characteristics. A "-X" indicates that the problem under consideration exhibits the opposite characteristic.

TABLE I

TYPOLOGY OF RELATED PROBLEMS

							Envir. transfer		
TYPOLOGY OF RELATED PROBLEMS	Modest benefits	Mechanism unknown	Low subj. probability	Potential catastrophe	Irreversibility	Latency	External costs	Collective risk	Internal benefits
Environmental risk (ozone depletion)	X	X	X	X	X	X	X	X	X
Environmental risk—major benefit (CO_2)		X	?	X	X	X	X	X	X
Drugs and food additives (red dye # 40)	X	X	X	X	X	X		X	X
Occupational accident (hand in machine)	X		X	X	X				X
Occupational exposure to "toxics" (BCME)	X	X	X	X	X	X			X
Public health (smallpox eradication)	-X	X	X	-X	X	X	-X	-X	-X

11. See text accompanying notes 82-84 *infra* for further discussion.

The benefits associated with an environmental gamble are not always relatively small but may be of the same order of magnitude as the potential costs. The most obvious example is the carbon dioxide (CO_2) "greenhouse" problem resulting from the burning of fossil fuel. The benefits of fossil fuel combustion are so large that precautionary steps are unlikely and perhaps unwarranted unless the probability of catastrophic climatological change is substantial. Aside from this characteristic—that the benefit is major rather than modest relative to the potential cost—the CO_2 greenhouse problem is like the "pure" environmental risk problem in its other characteristics.

Food additives and drugs also create problems exhibiting some, but not all, of the characteristics of environmental risk. While these problems are not strict environmental problems in the sense that both the hazards and the benefits are transferred through market mechanisms rather than through the environment, most problems associated with food additives and drugs do share the other characteristics of environmental risk. To illustrate, consider that virtually everyone in the United States is subject to the risk associated with Red Dye No. 40. When consumers are unaware of the hazards associated with market products or when the information is too complicated to evaluate, the distinction between an internal, voluntary transfer through a market mechanism and an external, involuntary transfer through an environmental mechanism becomes blurred. As a result of this less than clear distinction, there is a continuum of chemical risk problems ranging from market-transferred risks, such as pesticide residues on food, to environmentally-transferred risks such as lead in the air.

A similar continuum based on the degree of awareness of potential hazards exists for risks encountered in occupational settings. At one extreme, the risk of physical injury for a particular job is clear. Accident records over extended periods will provide a precise and actuarial definition of the risk. Workers who know the risk and have a choice of other jobs may bargain for wage premiums to compensate for the risk. Although the risk may be potentially catastrophic for the individual (*e.g.*, the risk of a disabling injury or death) the premiums are typically small on a daily basis because, even for hazardous jobs, the probability of a catastrophic accident on a given day is very small. To the extent that workers have information and choice, the market weighs the level of the probability against the size of the potential catastrophe. Since most physical accidents involve small numbers of people, the accidents are not collective risks.

The picture changes when the risks are less visible. Workers handling toxic chemicals have little or no information with which to evaluate the risk. Since the underlying toxic mechanism may not be understood and the effect may be latent, the risk takes on an external, involuntary character.[12]

12. For further discussion see R. Smith, The Occupational Safety and Health Act: Its Goal and Its Achievements 30-34 (1976).

The characteristics of environmental risk are also useful in the analysis of problems when the emphasis is on the societal benefits of an action rather than the risks. Certain public health problems are mirror images of environmental risk, but with the cost and the benefit roles reversed. Perhaps the best example is the United Nations smallpox eradication program. The smallpox problem, like the freon propellant example, can be treated as a "pure" case of two hypotheses.[13] Under one hypothesis, smallpox has no nonhuman carriers. If this hypothesis is true, the innoculation of humans could eradicate the disease for all time. Under the second hypothesis, there are nonhuman carriers of the virus. If this hypothesis is true, innoculation of humans makes possible control, but not eradication, of the disease.[14]

If eradication is successful, benefits external to markets accrue as an improvement in the quality of the environment. In contrast, the costs of the program are internal to markets. The costs are in the production of serum, health workers, transportation, and information gathering. The costs of the eradication program, over and above the ongoing costs of control, are very modest when compared with the potential benefits of eradication. Eradication is irreversible if successful, but there is a substantial time delay from the initiation of the program until its effects are learned. In preventive medicine the benefits are latent but the program costs are immediate.[15] As Table 1 indicates, the characteristics of the smallpox eradication gamble are similar to those of environmental risk, as schematized in Figure 3, but with the roles of costs and benefits reversed.

B. *Environmental Risk and Classical Pollution*

1. *Introduction*

The nine characteristics common to environmental risk problems also serve as a basis for distinction between environmental risk and more traditional environmental problems. Many environmental risk problems are the by-products of new, post-World War II technologies. Although certain long-existing environmental problems exhibit some of the characteristics of

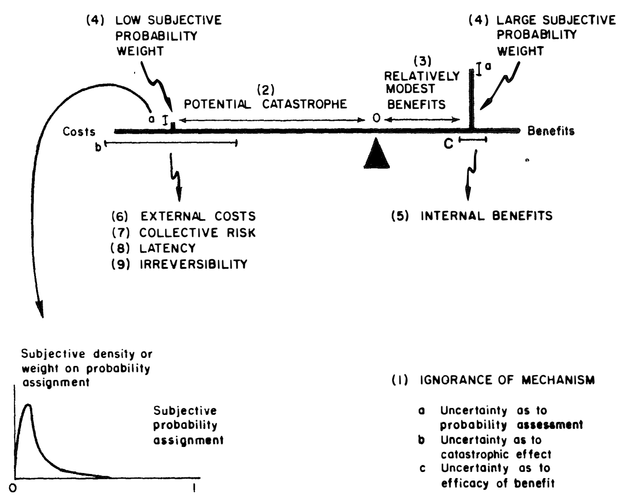
13. See note 2 *supra*.

14. An earlier program to eradicate yellow fever failed because there are monkeys that carry the disease.

15. Henderson, *The Eradication of Smallpox*, 235 SCIENTIFIC AM. 25-33 (1972). A reversal of roles of the characteristics of environmental risk is considered further in Part II of this Article.

FIGURE 3

Asymmetrical Balance of Environmental Risk



environmental risk,[16] there are differences in degree between many of the old, "classical" pollution problems and newer environmental risks. These differences can be described in terms of seriousness, relative costs, numbers, potency, timing, and visibility. Since the problems of environmental risk differ to such a large degree from classical pollution problems, we must

16. Manmade environmental risks often are compared with age-old environmental risks such as floods, earthquakes, tornadoes, and meteorites. *See, e.g.*, R. Kates, Assessing the Risk of Environmental Hazard, Scientific Committee on Problems of the Environment, Background Paper No. 4, Risk Assessment Workshop, Woods Hole, Massachusetts, March 31 - April 4, 1975, at 32-33, 39. While these comparisons can be highly useful, there are important differences discussed later in this Article in the assessment and confidence of probabilities, voluntariness and equity, role of human error, and benefit associated with the risk.

question the ability of our present legal and regulatory institutions to effectively manage and control these more recent environmental risk problems.

2. *Seriousness: Amenity Versus Life Threat*

The classical water pollution problems which dominated public and scientific concern until a few years ago were suspended solids, biological oxygen demand, eutrophicants, and detergents. Governmental regulation and resource commitment still are concentrated in these four areas, especially the first two. Although some classical water pollution problems, such as micro-biological contamination, directly affect human health, much of the concern over these four classical problems stems from the immediacy of their effect on amenities such as clear water and less algae. In contrast with the classical water pollutants are pollutants such as suspected carcinogens, mutagens, and heavy metals.[17] These "environmental risk" pollutants pose long-term, serious threats of uncertain likelihood to health and life. The Federal Water Pollution Control Act[18] provides for regulation of environmental risk pollutants, separate from classical pollutants, under the hazardous pollutants section.[19] However, this section until recently has been largely unenforced.[20]

The contrast between amenity value and life threat is slightly less pronounced in the case of classical air pollutants than in the case of classical water pollutants. These air pollutants, which continue to dominate governmental concern, are sulfur oxides, nitrogen oxides, particulates, hydrocarbons, oxidants, and carbon monoxide. Although these pollutants are perceived as direct health threats,[21] the emphasis had been on their short-term, milder effects, such as irritation to the eyes from oxidants, headaches from carbon monoxide, and respiratory distress, rather than on their long-term, potentially more severe health effects. A common assumption is that air pollution primarily affects the weak, with little effect on the healthy.[22]

17. *See, e.g.*, R. Harris, The Implications of Cancer-Causing Substances in Mississippi River Water (1974) (unpublished report for the Environmental Defense Fund).

18. 33 U.S.C.A. §§ 1251-1376 (West Supp. 1978).

19. *Id.* § 1317(a).

20. It was only after three environmental groups sued to compel enforcement and obtained an agreement from EPA to set standards that most chemicals were regulated. NRDC v. Train, 8 ERC 2120 (D.C. Cir. 1976) (consent agreement). The settlement agreement and amendments to the Act codifying many of its terms are discussed in Doniger, *Federal Regulation of Vinyl Chloride: A Short Course in the Law and Policy of Toxic Substances Control*, 7 Ecology L.Q. 497, 627-29 (1978).

21. In the early part of the 20th century, air pollution was widely perceived as a nuisance affecting amenities such as visibility. Gradually, the concern has shifted toward health, which became the dominant focus of the Clean Air Act.

22. According to Joseph Stuart, executive officer of the South Coast Air Quality Management District (Los Angeles Basin), "Southern California is not unhealthy for healthy persons, but can be unhealthy for residents with respiratory problems." Bernstein, *Smog Forecasts for Area Issued in New Format*, Los Angeles Times, Dec. 13, 1977, Part I, at 1, 29. This statement assumes that there is no long-term, latent hazard associated with Los Angeles air for presently healthy persons, or no gradual shift from the healthy to unhealthy category.

Similarly, the EPA air quality index (Pollutant Standards Index) focuses on short term effects. For example, its interpretation of the "very unhealthful" range is "significant aggravation of symptoms and decreased exercise tolerance in persons with heart or lung disease, with widespread symptoms in the healthy population." William F. Hunt, Jr., Office of Air and Waste Management, U.S. Environmental Protection Agency, The U.S. Environmental Protection Agency's Recommended Pollutant Standards Index (PSI), at 8 & Table 1 (paper presented at 69th Annual Meeting of the Air Pollution Control Association, Portland, Ore., June 29, 1976). Cancer risk is not a part of the interpretation of the various categories from "good" to "hazardous." The index is based upon the five classic pollutants: total suspended particulates, ozone, nitrogen dioxide, carbon monoxide, and sulfur dioxide; and the interpretation is based upon health effects, primarily short-term ones, of these five pollutants. Hydrocarbons, an aggregate class which includes many of the carcinogens and suspected carcinogens, are excluded from the index "because there are no direct health effects associated with the pollutant." *Id.* at 2.

In a preliminary study, KVB, Inc. of Tustin, California, identified 128 organics or groups of organics in the Los Angeles air basin, including n-dodecane, chloroform, dichloromethane, carbon tetrabromide, vinyl chloride, benzene, and isomers of xylene. H.J. Taback, T.W. Sonnichsen, N. Brunetz & J.L. Stredler, Control of Hydrocarbon Emissions from Stationary Sources in the California South Coast Air Basin: Final Report (1978) (study for California Air Resources Board to be released after ARB approval). Also in the Los Angeles area, Robert Gordon has identified 14 polycyclic aromatic hydrocarbons, including benzo(a)anthracene and benzo(a)pyrene, both carcinogens. Gordon, *Distribution of Airborne Polycyclic Aromatic Hydrocarbons*, 10 Envt'l Sci. & Tech. 370 (1976).

Although the classical air pollutants are directly associated with life threat and higher mortality, the relatively minor and short term effects of carbon monoxide contrast with the potentially global catastrophic greenhouse effect of carbon dioxide. It is noteworthy that while the classical pollutant, carbon monoxide, is presently controlled, its environmental risk cousin, carbon dioxide, is not. As in the case of water, other environmental risk air pollutants are carcinogens and mutagens.[23]

In the case of land contamination, there is a clear distinction between amenity value and life threat. Litter is an example of a classical pollutant; it is vexing, immediate, and in the aggregate expensive, but hardly life threatening. In contrast, the contamination by polybrominated biphenyls (PBB) of large areas of Michigan farmlands is a paradigm of an environmental risk gamble that resulted in tragedy.[24]

3. *Relative Costs: False Negatives and False Positives*

By definition, the potential costs of environmental risks are great and the benefits are generally modest. Correspondingly, there is asymmetry in the costs of making wrong decisions. For classical pollutants, the asymmetry of potential costs and benefits, and hence the potential costs of wrong decisions, are likely to be less pronounced than for environmental risk pollutants.

23. See note 22 *supra*.

24. *See generally* Carter, *Michigan's PBB Incident: Chemical Mix-Up, Leads to Disaster*, 192 Science 240 (1976).

The concept of false negatives and false positives helps to illustrate this distinction. In criminal law, two basic kinds of mistakes can occur: the jury (or judge) can find a guilty man innocent or an innocent man guilty. Testing chemicals for toxicity presents the same problem. Test results may indicate that a toxic chemical is not toxic or that a non-toxic chemical is toxic. The former type of error is called a false negative and the latter a false positive. In environmental risk assessment, the latter type of error is labeled a false alarm, but (perhaps significantly) there is no common name for the former error. For want of better terms, this discussion uses false negative and false positive to refer to these two types of errors in environmental risk decision making.

The costs of wrong decisions are asymmetric for environmental risk in inverse proportion to the potential net costs and benefits associated with each of the two hypotheses.[25] The cost of a false negative—deciding that the benign hypothesis is true when it is not—is much higher than the cost of a false positive—deciding that the catastrophic hypothesis is true when it is not. In the former case, the catastrophic results more than offset the modest benefits of erroneously accepting the benign hypothesis. In the latter case, the costs are equal only to the loss of modest benefits incurred by rejecting the benign hypothesis. The concepts of false negative and false positive, and the related asymmetric costs associated with decision making mistakes, are important in the analysis of environmental risk management.[26]

4. *Numbers*

One of the more striking attributes of classical pollutants is that there are so few of them. In the case of air pollution, the old National Air Pollution Control Administration singled out only a small number of pollutants for intensive study and regulation. There were just six "criteria" pollutants for which standards were written by 1971.[27] The prevailing opinion was that a small number of "defendable" standards was better than a larger number of less defendable ones.[28] Since then, the list of criteria pollutants has not expanded. The criteria pollutants are either common chemicals (sulfur oxides, nitrogen oxides, and carbon monoxide) or undifferentiated hydrocarbons, particulates, and oxidants (primarily ozone). A recent Environmental Protection Agency statement that air quality has substantially improved was based on this short list of criteria, or classical,

25. See note 2 *supra* and accompanying text.

26. See text accompanying notes 60-84 *infra*.

27. Notice of promulgation of air quality criteria documents for these pollutants was given as follows: 34 Fed. Reg. 1988 (1969) (particulate matter and sulfur oxides); 35 Fed. Reg. 4768 (1970) (carbon monoxide, photochemical oxidants, and hydrocarbons); 36 Fed. Reg. 1502 (1971) (nitrogen oxides). Ambient air quality standards for all six pollutants were established in 1971. EPA, *National Primary and Secondary Ambient Air Standards*, 36 Fed. Reg. 8186 (1971).

28. Interview with Vaun Newill, National Air Pollution Control Administration (1968).

pollutants.[29] From the standpoint of environmental risk, however, there are thousands of potentially hazardous chemicals requiring attention.

The situation is similar in the case of water pollution. While the classical focus of attention and regulatory control has been on just two pollutants, biological oxygen demand and suspended solids, from the standpoint of environmental risk there are hundreds of chemicals deserving attention. Until recently, synthetic organic chemicals have been neglected.[30]

The problems of research and control presented by the large number of environmental risk pollutants are compounded by possible interaction among these pollutants. Testing chemicals one by one often is not satisfactory because the interactions may be highly nonlinear. An otherwise harmless chemical may increase the potency of a carcinogenic chemical with which it comes in contact. For example, benzo(a)pyrene and benzo(a)anthracene are carcinogenic on mouse skin but their potency is increased a *thousandfold* in the presence of n-dodecane, which is noncarcinogenic by itself.[31] This is an example of a synergistic interaction, an interaction in which the total effect of two chemicals may be greater than the sum of the effects of the individual chemicals. Synergistic interactions create problems in the use of statistical inference to predict chemical effects. While each chemical may have a statistically insignificant toxic or carcinogenic effect on its own, its effect in combination may be significant. Analysis on an individual basis, a typical approach for classical pollution, can miss these combined effects.

5. *Potency*

Concentrations of environmental risk pollutants are typically much lower than concentrations of classical pollutants. Classical pollutants often are measured in parts-per-million (ppm), while environmental risk candidates often appear at the parts-per-billion (ppb) level. Experts in the management of traditional pollutants occasionally have dismissed environmental risk problems simply on the basis of their low concentrations.[32] However, a

29. *See* PROGRESS IN THE PREVENTION AND CONTROL OF AIR POLLUTION IN 1975, ANNUAL REPORT OF THE ADMINISTRATOR OF THE ENVIRONMENTAL PROTECTION AGENCY TO THE CONGRESS OF THE UNITED STATES IN COMPLIANCE WITH SECTION 313 OF PUBLIC LAW 91-604, THE CLEAN AIR ACT, AS AMENDED 8 (1976). Although it is encouraging to see downward trends in several of the classical pollutants, it is perhaps premature to conclude that "the air quality" is improving without a better understanding of the roles and trends of the several thousand candidate pollutants of environmental risk.

30. In the Mississippi River, for example, less than five percent of the organic fraction has been identified and only a fraction of this five percent has been tested for carcinogenity. Interview with Robert Harris, Environmental Defense Fund. *See also* text accompanying notes 18-19 *supra*.

31. It appears that all three chemicals are present in Los Angeles air. See note 22 *supra*.

32. *E.g.*, the response of Carmen Guarino, Philadelphia Water Commissioner and now a member of the EPA advisory panel on drinking water quality, to the finding that chloroethylether was present in Philadelphia water in concentrations of 0.5 ppb.: such a "minute quantity"

conclusion based upon experience with classical pollutants is misleading. Some carcinogens are potent at extremely low concentrations. Aflatoxin, for example, is carcinogenic at the 100 parts-per-trillion level.[33]

6. *Timing*

A defining characteristic of environmental risk is a latent period, with little or no warning of manifestation of adverse effect during the interim. In contrast, a number of the adverse effects of classical pollution are quickly apparent. Examples include algae from eutrophicants, suds from detergents, eye irritation from oxidants, and respiratory distress from other classical air pollutants. Legal and regulatory agencies respond more readily to problems with immediate manifestations, as opposed to problems whose effects become apparent only in the future.

7. *Visibility*

Some commentators have suggested that environmental risk problems are more visible than other environmental problems due to the dramatic nature of the potential catastrophe.[34] However, the long latencies, ignorance

is "like making a martini with one ounce of vermouth to 156 railroad tank cars of gin, . . . like the width of your fingers compared to the distance from Philadelphia to San Francisco." Heick, *Water Dept. Adds Tests, Treatment*, Philadelphia Inquirer, Apr. 19, 1975 (quoting Guarino).

In responding to The Implications of Cancer-Causing Substances in Mississippi River Water, *supra* note 17, I.M. Levitt, the Executive Director of Philadelphia's Mayor's Science and Advisory Council, wrote:

> The paramount question is: Are these chemicals concentrated in sufficient quantity to adversely affect our health? The answer in both cases, at least for Philadelphia, is that these chemicals do not exist in that abundance.
>
> [Harris] is as correct as I am when I say there is gold in the streets of Philadelphia. Spectrographic evidence would substantiate this statement. However, nobody is going to mine gold in the streets of Philadelphia. The concentration is simply too low.
>
> Similarly the presence of these toxic agents which are in the food we eat, the water we drink, the air we breathe, and, indeed, are present in some of the clothes we wear, are of such concentrations that they do not constitute a health hazard.

Levitt, *Philadelphia Water Gets an OK*, The [Philadelphia] Evening Bulletin, Mar. 14, 1975.

A part-per-billion is clearly a very small number, but it still means roughly 100 million trillion molecules of the carcinogen per liter of water. There is evidence that cancers start from single cells and it is believed that a single molecule may be enough to start a cancer. *See* Crump, Hoel, Langley & Peto, *Fundamental Carcinogenic Processes and Their Implications for Low Dose Risk Assessment*, 36 CANCER RESEARCH 2973, 2977 (1976); Cornfield, *Carcinogenic Risk Assessment*, 198 SCIENCE 693, 696 (1977).

33. 1 INTERNATIONAL AGENCY FOR RESEARCH ON CANCER, IARC MONOGRAPHS ON THE EVALUATION OF CARCINOGENIC RISK OF CHEMICALS TO MAN 149 (1972).

34. *See, e.g.*, Blair & Hoerger, *Toxic Substances Legislation—Regulators vs. Science* (pt. 2), 2 ENVT'L POL'Y & L. 138, 138-40 (1976).

Curiously, the large size of effect may actually work against salience by providing grounds for ad hominem attack on the basis of "hysteria" of the opponents of the risk. For just one example, Dixy Lee Ray criticized President Carter for his opposition to the Clinch River reactor: "It's all misunderstanding and hysteria . . . . I guess he was frightened in his mother's womb. The chances of a nuclear disaster in a power plant are one in five billion. You've got more chance of being squashed by a falling meteor." *Newsmakers: Dixy Ray Gives the President an Earful*, Los Angeles Times, Feb. 28, 1978, pt. 1, at 2. The confusion of subjective and objective probabilities is discussed at text accompanying notes 43-45 *infra*.

of mechanisms, and low subjective probabilities of effect characteristic of environmental risks suggest that these problems may actually be less visible than classical pollution problems.[35] Dr. Farley Fisher, head of the Early Warning Program of the Office of Toxic Substances of EPA, puts the matter forthrightly: "Few people in government are rewarded for 20 or 30 year predictions, especially when the probabilities are low. You are rewarded for pulling together existing information which foretells of a crisis six months from now with 100 percent certainty."[36]

Moreover, the visibility of a particular environmental risk problem may be obscured by the large number of these problems. Scientists, regulatory institutions, and the public may, for example, overlook the carcinogenicity of a chemical simply because there are too many other recognized carcinogens which warrant attention.

Further invisibility results from the extremely low concentrations associated with many environmental risk pollutants. Thus, environmental risk problems arguably are not visible enough. Without direct analysis of perception formation, the most that can be said is that important differences between the visibility of classical pollution and the visibility of environmental risk are a likely consequence of some of the characteristics of environmental risk.

II
DIFFICULTIES IN THE MANAGEMENT OF ENVIRONMENTAL RISK

A. *Introduction*

In the last section, environmental risk was distinguished from classical pollution in several respects. Yet the development of legal, regulatory, and economic institutions for the management and control of environmental problems has been primarily from the classical perspective. At the beginning of this Article it was mentioned that the defining charactistics of environmental risk, which set this class of problems off from others, make problems of environmental risk less amenable to institutional control. This section will discuss some of the problems encountered by existing institutions in the management of environmental risk and will propose alternatives designed to alleviate these problems.

35. In the SST debate there is both the environmental risk of ozone depletion and the classical pollution problem of sideline noise. In the Department of Transportation's Environmental Impact Statement and in the Environmental Defense Fund's opposition to the SST, the issue of sideline noise has been far more prominent than that of ozone depletion. *See generally* Comment, *Much to do About Concorde*, 6 ENVT'L L. REP. 10072 (1976). John Helligers of the Environmental Defense Fund attributes this emphasis to the subjective, uncertain nature of the probability assessments of depletion. Interview with John Helligers (1977).

36. Interview with Dr. Farley Fisher (1976).

B. Worst Cases

"Worst cases" are constructs useful in assessing the magnitude of risks associated with environmental risk problems. At its best, a worst case would provide a boundary beyond which there is a known zero probability of additional damage or cost. However, such a worst case could be defined only upon secure knowledge of the underlying mechanism. The uncertainty of mechanism associated with environmental risk necessitates the substitution of an ill-defined "credible" worst case for a well-defined worst case. Constructing worst cases useful for policy and management purposes is an art as yet not well developed. To date, there has been little discussion of techniques for constructing worst cases and little explicit methodology for their critique.

One of the few areas in environmental risk in which systematic efforts have been made to construct and analyze worst cases is nuclear energy. In a three million dollar, seventy man-year effort, the Rasmussen Report[37] meticulously estimated the probabilities for the sequences of events leading to a nuclear reactor core meltdown and subsequent release of radiation. The report attempted to include every possible "credible" sequence. However, just as the final report was released, estimating the aggregate risk for a fatality from nuclear accident to be 5×10^{-11} per reactor year,[38] a fire at the Brown's Ferry reactor nearly caused a core meltdown which could have caused thousands of fatalities.[39] Apparently, neither the sequence of design and human errors leading toward the meltdown nor the remedial action preventing the meltdown were modeled in the report. While the Rasmussen Report represents an enormous advance over previous efforts to define and estimate the likelihood of worst case accidents in nuclear power, there still is little information on which to base confidence in assessments of worst case risk for this application of nuclear technology.

An alternative to defining a worst case or credible worst case is to define the "most probable" case and estimate its potential cost and likelihood. However, this alternative may not always be possible. A twenty-one million dollar risk evaluation study by the Department of Transportation was not only unable to draw a clear boundary defining a credible worst case in the ozone depletion problem but also was unable to draw a conclusion as to the size and probability of the most probable case.[40] In the area of toxic chemicals, efforts to design a worst case in order to assess risk have been on a smaller scale, but with even less success.[41]

Difficulties in defining limits to the potential damage from environmental risks have led to a series of retreats from absolute worst cases to credible worst cases to probable cases. While these retreats are understandable, better management of environmental risks depends heavily upon the development of a methodology for constructing worst case scenarios.

C. Presumed Low Probabilities

The characteristics of modest benefits and potential catastrophe are incentives toward cautionary action. Yet, despite the potential results, the incentive to gamble often stems from the low subjective probability of the catastrophic effect.[42] Although the characteristic of low probability makes environmental risk gambles more acceptable, this characteristic leads to several difficulties in the management of environmental risk.

1. Subjective Versus Objective Probability

In considering the probabilities of potential catastrophes associated with environmental risks, comparisons sometimes are made with natural disasters. For example, the Rasmussen Report's estimate of the probability of fatality from one hundred nuclear power plants, one in five billion per year, was compared with the probability of fatality from meteorites, which was also estimated to be about one in five billion.[43] This comparison was used to suggest that the risks are roughly equivalent and that people should be as willing to live with one environmental risk as the other.

However, this comparison hides an important difference. The probability of a large meteorite striking the earth can be computed from an historical record going back millions of years. There is a solid actuarial basis for the probability estimate. Hence, a high degree of confidence is associated with

37. U.S. NUCLEAR REGULATORY COMMISSION, REACTOR SAFETY STUDY: AN ASSESSMENT OF ACCIDENT RISKS IN U.S. COMMERCIAL NUCLEAR POWER PLANTS, WASH-1400 (1975) (called the Rasmussen Report, after the director of the study, Norman C. Rasmussen).

38. *Id.*, *Executive Summary*, at 3 [hereinafter cited as *Executive Summary*].

39. See notes 53-54 *infra* and accompanying text.

40. *See* U.S. DEP'T OF TRANSPORTATION, CLIMATIC IMPACT ASSESSMENT PROGRAM (1975) (series of six monographs, available from National Technical Information Service, Springfield, Va.).

41. For example, data from In re Shell Chemical Co., 6 ERC 2047 (EPA, FIFRA Docket, 1974), which suspended the registration of dieldrin, can be used to illustrate the problems of constructing a worst case for toxic chemicals. Tests on mice indicated that at dose levels of 0.1 ppm there was an increase in benign and malignant liver tumors which had a tendency to spread to other parts of the body and especially to the lungs. 6 ERC at 2053. Furthermore, concentrations of dieldrin in the adipose tissue of the general human population have been found to be comparable to the levels exposed to 0.1 ppm of the compound. *Id.* at 2056. To construct a worst case, can it be inferred from the similarity in body burdens of dieldrin in the test mice and humans that dieldrin will eventually result in a similar increase in the total overall cancer rate or just in the liver cancer rate? Can we infer some other rate of increase? On the one hand the particular strain of mice used appears sensitive to liver cancer. On the other hand, a carcinogen affecting one site in a test animal can affect other sites in humans. Moreover, humans are sometimes more sensitive to carcinogens than laboratory animals. There is little to go on since even the link between feeding concentration and body burden is uncertain.

42. The asymmetry between internal benefits and external costs is another incentive to gamble, for the private decision maker and sometimes for the governmental decision maker as well.

43. *Executive Summary*, *supra* note 38, at 2-3.

the estimate for the probability of a meteorite fatality. The case of nuclear power is vastly different. Estimators of the probability of a nuclear power plant fatality are dealing with barely a thirty year record, with human design, and with human error; there is practically no actuarial basis for the probability estimate. The actual probability could be much higher or much lower. Dealing with probabilities which are uncertain is very different from dealing with probabilities which are known more precisely.[44]

Treating ignorance of mechanism as though it were randomness in a well-understood chance mechanism leads to thinking that probability estimates are more precise than they really are. The low degree of confidence characteristic of probability estimates for environmental risks makes management of these problems difficult, but this fundamental difficulty is better faced than conveniently forgotten.[45]

2. *Bias in the Subjective Assessment of Low Probabilities*

Due to uncertainty of mechanism, assessment of the probability of an adverse effect for environmental risk is unlike assessment of the probability that a five will turn up when a die is rolled. In the latter case, the mechanism is exposed and the probability of 1/6 can be derived from the symmetry of the die's six-sided figure. An alternate method for deriving this probability is the frequency of the five in repeated trials. Environmental risk presents a different problem; not only is the mechanism complicated and hidden, but there is only one "trial." Either the catastrophic hypothesis holds or it does not.[46] The important issue is: How will people respond in assessing probabilities when there is only a single trial for each gamble, there is no obvious symmetric chance mechanism from which to reason, and the adverse event is unlikely to occur?

Experiments by Alpert and Raiffa and by Tversky and Kahneman offer an insightful approach to these questions.[47] Their results suggest that people often underestimate the probability of rare events. The investigators began with a list of "almanac" questions such as: "How many foreign cars were imported into the United States in 1968?" For each question, the test subjects were asked to make an estimate so high that they would believe there was only a one percent probability that the true answer would exceed their estimate. They were also asked to make an estimate so low that they would feel there was only a one percent probability that the true answer would be lower than their estimate. If this construction of rare events were accurate and unbiased, the factual answers would lie outside these high and low estimates (confidence intervals) about two percent of the time. However, in the experiments the factual answers were outside the confidence intervals forty to fifty percent of the time. Constructing rare events to a given probability is not the same as assigning probabilities to rare events; nevertheless, these experiments suggest that people may systematically assign insufficiently low probabilities to rare events.

If people assign insufficiently low probabilities to rare events, the subjective probability assigned to the potential catastrophic result associated with an environmental risk may be too low. This problem could lead to many catastrophic surprises in environmental risk management. Further research is needed along these lines in order to understand the bias in subjective assessment of low probabilities.

3. *Rarity of Effect and Predictive Power*

The assessment of the probability of a potential environmental catastrophe is a sequential process. An initial assessment is based on a limited understanding of mechanism. As new information is gathered, the initial assessments of probability are modified. Tribe discusses the difficulties encountered in using new information to modify initial probability assessments of guilt in the context of criminal trials.[48] He argues persuasively that people tend to leave out important, often overriding factors because of the particular institutional goals and constraints of a trial setting.

What happens to environmental risk where the initial assessment of "guilt" for some chemical may be considerably less than 0.1? There is strong experimental evidence that at the low end of the spectrum people *overestimate* the impact of new evidence.[49] The degree of rarity, or low

44. In an alternate usage, the term "risk" is reserved for situations where the underlying probabilities can be precisely estimated, as in games of chance; "uncertainty" is then reserved for situations where the probabilities can only be assessed imprecisely. *See* F. KNIGHT, RISK, UNCERTAINTY, AND PROFIT 19-20, 197-232 (1921). To avoid confusion, this usage is avoided in this Article.

45. Moreover, by treating ignorance of mechanism as though it were the same thing as randomness in a well understood mechanism, one may miss important clues which may reduce the uncertainty of mechanism. The path of tornadoes and the fall of meteorites are considered largely chance phenomena. The aerodynamics of the former and the celestial mechanics of the latter are thought to be understood about as well as they might be. To have approached the problem of earthquakes in the same spirit would have been a mistake. The prediction of earthquakes has made great gains in the past few years, because the research has focused on our ignorance of the underlying deterministic aspects of mechanism. Treating ignorance of mechanism as though it were the same as a well understood chance mechanism can easily deflect us from gathering highly useful information for environmental risk management. Such treatment leads to different kinds of experiments and different approaches to resolving or living with uncertainty.

46. See note 2 *supra* and accompanying text.

47. These experiments are described in Slovic, Kunreuther & White, *Decision Processes, Rationality, and Adjustment to Natural Hazards*, in NATURAL HAZARDS: LOCAL, NATIONAL AND GLOBAL 187 (G. White ed. 1974).

48. Tribe, *Trial by Mathematics: Precision and Ritual in the Legal Process*, 84 HARV. L. REV. 1329 (1971).

49. Tversky & Kahneman, *Judgment under Uncertainty: Heuristics and Biases*, 183 SCIENCE 1124, 1125 (1974).

probability, of environmental effect dilutes the predictive power of testing and of new information in a manner often unrecognized.

For illustration of this last point, suppose that 60 of 10,060 chemicals are highly carcinogenic to humans and that a test has been developed which in the following sense is highly reliable. The test scores positive for carcinogenic chemicals ninety-five percent of the time and scores negative for noncarcinogens ninety-four percent of the time. A chemical, drawn from the 10,060, tests positive. What is the probability that the chemical is carcinogenic? Many people are surprised to learn that the actual probability, which can easily be derived from Bayes Theorem, is only 0.09.[50] As suggested by Kahneman's research,[51] people often expect too much in the way of proof from present tests and research techniques in problems of environmental risk.

An unfortunate generalization arises directly from the underlying mathematics of this example: as the probability of an environmental effect approaches zero, the probability of a positive test being falsely positive approaches one. In other words, as an environmental risk problem takes on more of the characteristics of a zero-infinity dilemma, the probability of a false positive becomes higher. Simultaneously, the management problem becomes tougher because the more an environmental risk problem exhibits the zero-infinity characteristic, the greater is the need to prevent a false negative—in this instance, the labeling of a guilty chemical as innocent.

4. *Human Error*

Human error plays an especially important role in the assessment of probabilities for environmental risks. The most likely cause of the polybrominated biphenyl (PBB) tragedy in Michigan was human error. It appears that several bags of "Firemaster" (PBB) were mistakenly mixed into "Nutrimaster" (a cattle feed supplement consisting of magnesium oxide) in part because Michigan Chemical Company, the producer of both chemicals, had run out of marked bags.[52] Similarly, the Brown's Ferry fire, which nearly caused a reactor core meltdown,[53] was started by operators using a candle to check for an air leak.[54] In retrospect, it is clear that the design which made the wires to the main operating system and the emergency system vulnerable to the same fire was also a human error.

Large and complicated systems often are associated with environmental risks. In such systems, the chances for human error are multiplied enormously. A fundamental and very difficult question for environmental risk management is how to model and control human error effectively.

D. *Acceptable Risk*

Even if the probability of an environmental risk were well defined, our legal, regulatory, and economic institutions must still decide what degree of risk is acceptable. Although there are several approaches for defining acceptable risk, there is little agreement on what is the best approach. This ambiguity presents a major difficulty in managing environmental risk. A few of the approaches are discussed below.

1. *Inferences from Behavior*

Acceptable risk is sometimes defined in terms of risks that people are observed to accept. Starr suggests that there are natural boundaries to risk, delineated by the high risk of communicable disease mortality and the low risk of natural disaster mortality, between which people accept exposure to

50. The reason for the 0.09 probability can be seen as follows. The test is described by its two characteristics: its ability to classify truly carcinogenic chemicals as carcinogens (it does this with probability 0.95), and its ability to classify truly noncarcinogenic chemicals as noncarcinogenic (it does this with probability 0.94). Consider the second test characteristic first. If the test were applied to the entire group of 10,000 noncarcinogens, roughly 94% or 9400 chemicals would test negative (there would be some variation about this mean or expected value). These are true negatives. The remaining number, about 600 or 6% of the 10,000 noncarcinogens would test positive. These are false positives. Next consider the first test characteristic. If the test were applied to the much smaller group of 60 noncarcinogens, roughly 95% or 57 would test positive. These are true positives. Unfortunately, when a positive test is observed in actual practice there is no way of knowing which group the chemical is drawn from—the group of roughly 600 false positives or the smaller group of roughly 57 true positives; all that is known is that the chemical is drawn from the combined pool of about 657 positives. The probability that a chemical which tests positive is in fact a carcinogen is only 57 chances out of 657 chances, or 0.09. The rarity of effect tends to swamp the discriminative power of the test.

For a derivation of Bayes Theorem and discussion of an almost identical example involving carcinogenesis, *see* E. PARZEN, MODERN PROBABILITY THEORY AND ITS APPLICATIONS 119-21 (1960). For more discussion of the use of Bayes Theorem in decision theory, see H. RAIFFA, DECISION ANALYSIS: INTRODUCTORY LECTURES ON CHOICE UNDER UNCERTAINTY (1970).

51. *See* Tversky & Kahneman, *supra* note 49, at 1125.

52. Carter, *supra* note 24, at 240.

53. Henry Kendall, Professor of Physics, Massachusetts Institute of Technology, interviewed in "Incident at Brown's Ferry," NOVA #406, Feb. 23, 1977, transcript at 12 (television program, WGBH-TV, Boston, Mass.).

54. *The Power of a Candle*, 20 NUCLEAR ENGINEERING INT'L 391 (1975). The incident is more thoroughly described in Rippon, ***Brown's Ferry Fire***, 20 NUCLEAR ENGINEERING INT'L 461 (1975). The fire started by the candle spread into control and instrumentation wiring, leading to the loss of several emergency cooling systems and, after one reactor was shut down, to increased temperatures and pressures which could not be controlled with some other backup systems. The fire forced manual shutdown of both reactors at the Brown's Ferry site, and although other backup cooling systems remained operational, all relied on manual controls. The industry response to the accident stressed the fact that no catastrophe actually had occurred:

> [More stringent requirements for separation of emergency features systems] would seem to answer any criticism that there might be of nuclear installations, but it could involve a formidable amount of backfitting if applied to all operating power stations. Bearing in mind that the Brown's Ferry reactors were shut down and maintained in a cooled state without any harm to personnel or equipment, and that there were still alternative systems available to maintain the reactors in a safe state, it would be wrong to react over hastily in the enforcement of the new control separation criteria in existing plants.

Id. at 461.

involuntary risk.[55] Such benchmark comparisons have been used in studies of nuclear power and appear to be a common approach taken by engineers.[56] Economists have suggested that premiums for hazardous occupations define acceptable risk.[57] However, for risk markets, whether implicit or explicit, to work well enough to define acceptable risk, the nature of the risks must be understood and the acceptance must be voluntary. There is considerable doubt that these conditions are met in cases of environmental risk.[58] An alternative to market or field data on actual behavior or risk acceptance is psychometric experimentation, which asks people to evaluate risks in laboratory settings. This approach, which might be expected to yield concepts of acceptable risk, instead has only cast further doubt on the ability of people to evaluate risks.[59]

Inferences from behavior often carry the faintly Panglossian assumption that whatever is accepted is acceptable. The following three approaches rely less on inference from behavior and are, therefore, more prescriptive.

2. *Limiting False Positives*

This approach, which is the most common approach for risks subject to governmental regulation and court proceedings, starts with the assumption that there is no risk and requires that a hazard be proved beyond some standard. Under this approach, by definition, if the standard of proof is not met, then the risk is acceptable. The burden of proof is placed on those seeking precautionary action. An example of this perspective is a comment by the Water Commissioner of Philadelphia: "If future research proves a true link between water-borne organics and cancer in humans, Philadelphia will spend whatever is necessary to cope with the problem."[60] Initially, this

55. *See* Starr, Rudman & Whipple, *Philosophical Basis for Risk Analysis*, 1 ANN. REV. ENERGY 629, 629-30 (1976), *critiqued in* H. Otway & J. Cohen, Revealed Preferences: Comments on the Starr Benefit-Risk Relationships (International Institute for Applied Systems Analysis [Laxenburg, Austria] Research Memorandum, March, 1975).

56. *See, e.g.*, *Executive Summary, supra* note 38, at 1.

57. *See* R. Thaler and S. Rosen, The Value of Saving a Life: Evidence from the Labor Market (paper presented to National Bureau of Economic Research Conference on Income and Wealth, Household Production and Consumption, Washington, D.C., Nov. 30, 1973).

58. *Cf.* Lave, *Product Safety: An Economic View*, ASTM STANDARDIZATION NEWS, Feb. 1963, at 14-21 (stating that product safety regulations may fail to determine acceptable risk). *See generally* the discussion of drugs and food additives and occupational hazards in the section on typology of related problems at text accompanying notes 11-12 *supra*.

59. *See, e.g.*, Tversky & Kahneman, *supra* note 49. *See also* Slovic, Kunreuther & White, *supra* note 47, at 191-99. Robert Kates reports on studies in which less than half the public could translate the National Weather Service's probability of precipitation into qualitative rankings of more and less likely. *See* R. Kates, *supra* note 16, at 31-35.

60. Letter from Carmen Guarino, Water Commissioner, City of Philadelphia, to the editor of the *American City Magazine* (Mar. 7, 1975). Eric Johnson, head of the American Water Works Association, also advocated the approach limiting false positives: "Until it [chloroform in drinking water] is proved to be bad, I'd prefer to believe it isn't. Municipalities have plenty of things to spend their money on." Hornblower, *EPA Plans Rules on Water Purity*, Los Angeles Times, Dec. 27, 1977, pt. 1, at 1, 15, col. 1 (quoting Johnson).

perspective appears reasonable, especially in view of the sweeping remedial action premised upon meeting the standard of proof. This approach also suggests caution, in that open-ended expenditures for control will not be spent unnecessarily.[61] However, the approach of limiting false positives, although often effective in defining acceptable risk for classical problems, has questionable value for the management of environmental risk.

Limiting false positives is common in statistical studies, including studies of environmental risks. The tested hypothesis is usually a hypothesis of no effect. A statistical procedure is chosen which limits the chance of a false positive, the erroneous rejection of the no-effect or null hypothesis and the concomitant finding of an effect, to some prescribed level, usually one or five percent in practice. If the null hypothesis is rejected, a decision is made that there is an effect; if the procedure fails to reject, there is no decision as to the existence or nonexistence of the effect ("judgment is reserved"). In common practice, however, after a failure to reject a no-effect hypothesis, and perhaps during the time further investigations are undertaken, decision makers treat the effect as though it were nonexistent and take few precautionary steps. Moreover, sometimes the distinction between the failure to find an effect and the finding of no effect is simply ignored. In that case, a negative finding leads to a negative conclusion.[62]

The distinction between the failure to find an effect and the conclusion that there is no effect is not trivial. This distinction is so important, especially in the area of environmental risk management, that its blurring can be given the name *fallacy of false negative*. The fallacy is to believe that a decision procedure designed to limit false positives necessarily yields *any* conclusion about the nonexistence of an effect when there is a negative finding.

A simple illustration is helpful. A pail contains tennis balls, all white except for the possibility of a single yellow ball. The problem is to determine whether the pail contains the yellow ball. In the decision procedure an observer is allowed to look only at the top layer. Under the procedure the

61. See note 74 *infra* for the different evaluation following from the expected value approach.

62. One of the important studies of carcinogens in drinking water provides an example of a negative conclusion being drawn from a negative finding. In his first study of carcinogens in Ohio drinking water, Buncher found some statistically significant results but enough insignificant results so that he concluded that he could not reject the no-effect hypothesis. C. Ralph Buncher, Cincinnati Drinking Water—An Epidemiologic Study of Cancer Rates (1975). In transmitting the study to the Cincinnati City Council, the City's Health Commissioner concluded, from the inability of the statistical procedure to find an effect, that there was no effect. He wrote: "It was concluded that these two events [the high cancer rates in Cincinnati and what he termed 'minute' quantities of organic compounds in the drinking water] were unrelated." Letter of transmission from Arnold Leff to City Council of Cincinnati (Nov. 14, 1975). This inference, unjustified in statistical theory, became an embarrassment after Buncher's second study, which, using a larger data base, rejected the no-effect hypothesis and found an effect. Buncher, *Drinking Water as an Epidemiological Risk Factor in Ohio*, in 4 COLD SPRING HARBOR CONFERENCES ON CELL PROLIFERATION, ORIGINS OF HUMAN CANCER (1977).

test scores positive if the observer sees a yellow ball in the top layer; the test scores negative if the observer does not see a yellow ball in the top layer. In this simple procedure the probability of a false positive is limited to zero. If there is no yellow ball in the pail, the observer will not see one in the top layer; there is no way for the test erroneously to find an effect when it does not exist. However, the probability of a false negative, a conclusion that the ball is not present when it actually is, can vary all the way from zero to one, from never to always, depending on the number of layers of balls.

If the pail is only one layer deep, the probability of a false negative is zero. In this situation, if the observer does not see the yellow ball, it is not in the pail. In this extreme case, there is no distinction between the failure to see the yellow ball and the finding that there is no yellow ball in the pail. However, if the pail is several layers deep, the distinction becomes important. There exists the possibility of not seeing the yellow ball even though it is present. If the pail is several hundred layers deep, the chance of a false negative, not seeing the ball even though it is in the pail, is nearly 100 percent.

Thus, as the depth of the pail is varied from a single to an infinite number of layers, the probability of a false negative varies from zero to one, even though the chance of a false positive is always held to the same limit, zero. As can be seen by this illustration, limiting the chance of a false positive does not by itself yield any conclusion regarding the chance of an effect not being present upon a negative finding.

This does not mean that decision makers can never draw negative conclusions from negative findings. However, in order to do so the structure of the problem must be investigated directly. The less uncertain the structure (*i.e.*, the more information available), the more likely it is that a negative finding will lead to a valid conclusion. In the illustration, the important structure is the depth of the pail or the ratio of the balls that can be seen to those that cannot. If the observer is allowed to see nine-tenths of the balls and still does not see the yellow ball, he can conclude, with only a ten percent chance of a false negative, that the yellow ball is not present. Thus, a negative conclusion has been established from a negative finding.

In many decision problems the pail may be shallow, so a negative finding will impart a good deal of information about the nonexistence of effect. But in environmental risk, with long latencies and diffusion of effects, effects are well hidden. For these risks, the pail is deep and careful investigation is required to support a negative conclusion drawn from a negative finding. In one model of carcinogens in drinking water, where the chance of a false positive was held to 5 percent, the chance of a substantial effect going undetected was still 40 percent.[63]

63. Harris, Page & Reiches, *Carcinogenic Hazards of Organic Chemicals in Drinking Water*, in *id.* The model is developed as a simple illustration of the problems of statistical

The attuned reader will find the fallacy of the false negative ubiquitous in legal, regulatory, and statistical reasoning. When the press reports that saccharin has been in use for 70 years without a single human cancer death proven as a result of its use, the suggested inference is that this is evidence of saccharin's non-carcinogenicity to humans. Before drawing this inference, regulatory institutions and other decision makers should investigate the likelihood of detecting saccharin carcinogenity even if, for example, it should contribute 700 to 1,000 extra cancer deaths a year. This type of question is rarely posed or investigated in statistical and other studies of environmental risks.[64] Without its investigation, negative findings are largely devoid of meaning, especially for environmental risks where the probabilities of false negatives are likely to be substantial. For a meaningful interpretation of a negative finding, there must first be an explicit investigation of the power of the statistical or other decision procedure to detect hidden effects.[65]

3. *Limiting False Negatives*

Limiting false positives is the guiding principle of criminal law. The objective is to limit the chance of a false conviction. The common-sense justification for this objective is that it is better to free a hundred guilty men than to convict one innocent man. A rough translation is that a false positive (false conviction) is a mistake a hundred times more costly than a false negative (false acquittal). A principal reason for this is that liberty is a primary good, *i.e.*, a good for the deprivation of which there is no adequate compensation.[66] The asymmetrical results achieved by the criminal justice system are intentional and follow from the exceptional value placed on liberty.

A comparison of criminal law with environmental risk, however, suggests an important difference. The costs of false negatives and false positives are asymmetric for environmental risk as well, but the asymmetry is in reverse order. For environmental risk, the asymmetrically high cost arises from a false negative; in criminal law from a false positive. Similarly,

power when effects are hidden, in the sense that they are rare and relatively small compared with background. In statistics, "power" is the probability that a test will find an effect if it exists. It is one minus the probability of a false negative.

64. Marvin Schneiderman, Associate Director, Field Studies and Statistics Institute, National Cancer Institute, has emphasized the need for investigation of statistical power. Letter from Marvin Scheiderman to Dr. Philippe Shubik, Director, Eppley Institute for Research in Cancer, University of Nebraska (June 28, 1976), commenting on P. Shubik, General Criteria for Assessing the Evidence for Carcinogenicity of Chemical Substances (unpublished memorandum). The concept of "statistical power" is defined in note 63 *supra*.

65. In the case of Cincinnati drinking water, Buncher specifically warned against the fallacy of the false negative, although he did not investigate the probability of a false negative. *See* Buncher, *supra* note 62, at 114-15.

66. *See generally* J. RAWLS, A THEORY OF JUSTICE 61-65 (1971). Rawls defines a primary good as a good "that every rational man is presumed to want." *Id.* at 62.

just as a primary good, liberty, is an important concern in criminal law, so another primary good, health, is an important concern in environmental risk management, but again the roles are reversed. Typically, public health is adversely affected under a false negative for environmental risk, while liberty is adversely affected under a false positive for criminal law.

The analogy between criminal law and environmental risk requires that the roles of negatives and positives be reversed. If the emphasis on limiting false positives for criminal law is sensible and based on the asymmetry of costs of wrong decisions and the possible deprivation of a primary good, then the implication is that a decision procedure based upon limiting false negatives is more appropriate for environmental risk than one based upon limiting false positives.

A common justification for the usual approach to environmental risk, which focuses on limiting false positives, is that because it is impossible to prove absolute safety, the burden must shift to a proof of danger. This is a *non sequitur* in environmental risk because usually it is impossible to prove either safety or danger with finality.

This does not suggest that acceptable risk should be defined solely in terms of limiting just one type of error. Nonetheless, since the previous focus of environmental risk management has been on limiting false positives, some redress toward limiting false negatives is now in order. Shifting burdens and standards of proof helps accomplish this goal. The Delaney Clause amendment is a conspicuous example of a procedure which ostensibly attempts to limit false negatives in the control of carcinogenic food additives.[67] However, the amendment has eliminated only two minor additives in 19 years—MOCA and Flectol II—so there is considerable question whether it provides substantial protection against false negatives.[68]

Focusing more attention on the need to limit false negatives brings us back to the importance of modeling the risks and hypotheses, including "credible" worst case modeling. It is clearly infeasible to take precautionary action for each conceivable environmental risk; there would be too many. Requiring some sort of model of the risk provides an entrance barrier against the flood of conceivable risks for which precautionary action should be evaluated. Because of the nature of environmental risk it is senseless to require actual proof of harm; the barrier should be no more than a reasonable

67. 21 U.S.C. § 348(c)(3)(A) (1970) (the Delaney Clause). *See generally* Blank, *The Delaney Clause: Technical Naïveté and Scientific Advocacy in the Formulation of Public Health Policies*, 62 CALIF. L. REV. 1084 (1974); Oser, *An Assessment of the Delaney Clause After 15 Years*, 29 FOOD DRUG COSM. L.J. 201 (1974). The Delaney Clause states:

> no additive shall be deemed to be safe if it is found to induce cancer when ingested by man or animal, or if it is found, after tests which are appropriate for the evaluation of the safety of food additives, to induce cancer in man or animal . . . .

21 U.S.C. § 348(c)(3)(A) (1970).

68. M. Suter & W. Muir, Survey of Toxic Substance Regulation of the U.S. Federal Government 93 (1977) (draft).

basis within the context of the model for believing that there is a risk of harm. The risk itself may be small.

For many environmental risks it is difficult even to define a candidate which might be or might become a false negative, much less to design an institutional structure which would take the chance of a false negative into account as well as the chance of a false positive. The search for environmental risk candidates and false negatives remains an underdeveloped art, and each case is different. The following example illustrates the art and development of a reasonable basis for concluding that there is an environmental risk, in this case within the context of a model of chemical carcinogenesis. In the 1972-74 period, Robert Harris identified carcinogens in drinking water as a major environmental risk. There were several clues, some positive and some negative.[69]

Among the positive clues were:

(i) The original determination of safety was made under one set of circumstances, but when the circumstances changed, the determination of safety was maintained with little or no re-examination. At the turn of the century, infectious disease was a problem and the purification system of the time was designed to filter and kill bacteria. The acute nature of this problem facilitated rapid testing. The resulting corrective system, however, was not designed to trap and eliminate heavy metals and industrial organic chemicals, which were in low concentrations at the time and not perceived as a problem. When heavy metals and industrial organics grew enormously in concentration, little was done to inquire whether the old standard of safety still applied.

(ii) Several chemicals found in drinking water are known carcinogens.[70] Evidence of the presence of carcinogens was available ten to twenty years ago. Thus, the question is not whether there are carcinogens in drinking water, but whether the carcinogens in drinking water are in sufficiently high concentrations to have an impact on cancer rates.

(iii) Scientists have known for at least a decade that cancer rates are elevated along industrialized rivers such as the Mississippi.

69. R. Harris, *supra* note 17. *See also* Harris & Brecher, *Is the Water Safe to Drink?*, 39 CONSUMER REP. 436, 538, 623 (1974) (three part series).

70. In 1972, EPA released a study of the lower Mississippi River which identified in the raw or treated drinking water, mercury, arsenic, lead, copper, chromium, cadmium, zinc, phenols, and cyanides, among others. Three compounds in the treated drinking water were identified as carcinogens—chloroform, benzene, and carbon tetrachloride—and hexachlorobenzene, zylene, ethyl benzene, and dimethylsulfoxide were suspected carcinogens at the time. Region VI, U.S. Environmental Protection Agency, Industrial Pollution of the Lower Mississippi River in Louisiana (Apr. 1972). *See* R. Harris, *supra* note 17, at 6. For earlier work, see Middleton & Rosen, *Organic Contaminants Affecting the Quality of Water*, 71 PUB. HEALTH REP. 1125 (1956); W. HUEPER & W. CONWAY, CHEMICAL CARCINOGENESIS AND CANCERS 659-60 (1964).

(iv) As long ago as 1963, Hueper and Payne showed that extracts of industrialized river water caused cancer in mice.[71]

There were also some negative clues:

(i) There are many chemicals in drinking water. If a number of these chemicals are harmful, they are likely to have different effects (cancer, birth defects, liver toxicity, etc.). In the aggregate, the effects will tend to diffuse and mask each other. Many different effects are harder to disentangle than one large one. Furthermore, long latencies are usually associated with waterborne carcinogens, because they are ingested in low concentrations over long periods of time. During these long periods of time, people move, drink from different sources of water, and die of other causes. Moreover, the contaminants in a given water supply change. In other words, there were strong reasons to believe that if the effects existed, they would not have come to light on their own.

(ii) In the past decade, exposure to industrial organic chemicals has greatly increased. Much of the effect could be in the future and thus further hidden from present view.

A survey of the process of identification of environmental risks is not comforting. It appears that the process is often haphazard, not only in the case of carcinogens in drinking water, where the identification occurred outside formal institutions designed to safeguard water, but also in other cases, such as the identification of PBBs, Thalidomide, and Tris as environmental risk candidates.[72] Because of the lack of systematic, effective procedures for identifying potential false negatives, legal and regulatory agencies have not recognized, much less controlled, many environmental risk hazards.

4. *Balancing False Positives and False Negatives*

An approach toward a definition of acceptable risk and the design of legal and regulatory institutions in managing environmental risk need not be restricted to choosing between limiting either false positives or false negatives. Instead, it can seek to weigh the risk of one wrong decision against another. The most frequently proposed means to accomplish this is to make the decision to regulate or not to regulate an environmental risk by comparing the cost of a false negative weighted by its probability with the cost of a false positive weighted by its probability, and choosing the alternative with the lower weighted cost. This method of minimizing the expected cost of a wrong decision is simply another version of the expected value criterion.[73] There will still be some risk of making a wrong decision, and this mixed approach offers its own definition of acceptable risk. Under this approach, once a decision is chosen to minimize the expected cost of a wrong decision the remaining risk is acceptable. Application of this approach requires four pieces of information: the cost of a false negative; the cost of a false positive; and the probability of each.

In its extreme, the approach of limiting false positives requires positive evidence of "dead bodies" before acting. Consideration focuses on the probability of a false positive. It does not matter that, as is typical with environmental risk, the cost of a false negative may be much higher than the cost of a false positive or even that the probability of a false negative may be substantially higher than the probability of a false positive. In the approach limiting false negatives consideration focuses on the probability of a false negative. Although the approach limiting false negatives is more suited to the characteristics of environmental risk than is the approach limiting false positives, expected value minimization is a distinct improvement over either because expected value minimization takes into account four relevant factors instead of just one and it provides a balance between the two types of error.[74]

The cancer test in the previous illustration provides an example of the advantage of using expected value minimization.[75] From one point of view

71. Hueper & Payne, *Carcinogenic Effects of Adsorbates of Raw and Finished Water Supplies*, 39 AM. J. CLINICAL PATHOLOGY 475 (1963).

72. The role of PPBs was identified by accident after a chromatograph was inadvertantly left on during lunch. *See* Carter, *supra* note 24, at 241. Thalidomide was identified some time after two deformed infants were exhibited at the annual meeting of pediatricians in Kassel, Germany in 1960. *See* Taussig, *The Thalidomide Syndrome*, SCIENTIFIC AMERICAN, August 1962, at 29. Attention turned to Tris several years after massive exposure, when Mike Prival and Farley Fisher of the Office of Toxic Substances, EPA, asked what tests had been done on the chemicals in children's pajamas. At that time the Office of Toxic Substances had no jurisdiction over the chemical. Interview with Mike Prival (1976).

73. This can be seen by listing the four possibilities: (1) the environmental gamble is rejected when the catastrophic hypothesis is true (true positive), (2) the environmental gamble is accepted when the catastrophic hypothesis is true (false negative), (3) the environmental gamble is rejected when the benign hypothesis is true (false positive), and (4) the environmental gamble is accepted when the benign hypothesis is true (true negative). Possibilities (2) and (3) are the wrong decisions. If the environmental gamble is accepted, there is the risk of (2) with cost $(C-B)$—the costs are somewhat offset in the "modest" benefits of the environmental risk which accrue even under the catastrophic hypothesis. In terms of note 4 the probability of this loss is p and expected cost $p(C-B)$. If the environmental gamble is rejected, there is risk of the wrong decision (3) with cost B, the benefits unnecessarily foregone, probability $(1-p)$, and expected cost $(1-p)B$. The expected cost rule, to minimize the expected cost of wrong decisions, directs us to accept the gamble if $p(B-C)<(1-p)B$, which is the same condition as in note 4 *supra*.

74. In the case of drinking water and carcinogens, with all four factors in consideration, the increase in cancer is the open-ended cost. The increase might be as little as zero, or 15 percent, as preliminary regression analysis has suggested, or with low probability, even higher. *See* Page, Harris & Epstein, *Drinking Water and Cancer Mortality in Louisiana*, 193 SCIENCE 55 (1976). Matched against these high costs of cancer, engineering estimates of the cost of control, by carbon filtration, are bounded at lower levels with much greater confidence.

The cost of precautionary water treatment is an internal cost (internal to the municipal budget), while the cost of cancer is an external cost (external to the municipal budget). Internalizing costs is difficult for municipalities, just as it is for firms.

75. This illustration is presented at text accompanying notes 49-51 *supra*.

the test created more, not less, uncertainty.[76] Before the test, the chance that the chemical chosen was noncarcinogenic was 99.5 percent; after the test, it was 91 percent. However, there is clearly a gain in information from performing the test, a gain which may be decisive from an expected value standpoint. If the cost of a false negative is 12 times the cost of a false positive, then control is warranted under the expected value criterion. This is true even though the probability that the chemical is carcinogenic is only 9 percent. In this illustration, and probably in many practical instances, the expected value criterion of acceptable risk is more conservative than are existing approaches, which focus on limiting false positives. It is important to note that when the expected value approach is used, the standard of proof is tailored to the magnitude of potential wrong decisions.[77]

The expected value approach does not require that each environmental risk be regulated, or not regulated, on the sole basis of a detailed and quantified cost-benefit analysis. To do so would ignore several of the important characteristics of environmental risk.[78] Alternatively, in order to come closer to a minimum expected cost of wrong decisions, it is necessary to adjust the rules of the decision process—the standards and burdens of proof, the rules of liability, the incentives for the generation and validation

76. In this point of view, the closer a probability is to zero or one the more certain we are about the event taking place or not; the closer the probability is to 0.5 the more uncertain we are about the event taking place.

77. This is essentially the approach adopted in the Toxic Substances Control Act, Pub. L. No. 94-469, 90 Stat. 2003, 15 U.S.C.A. §§ 2601-2629 (West Supp. 1977), the purpose of which is to control "unreasonable risks" of chemicals and chemical mixtures. What is not an unreasonable risk is an acceptable risk. *See* Slesin & Sandler, *Categorization of Chemicals Under the Toxic Substances Control Act*, 7 ECOLOGY L.Q. 359, 365-71 (1978). Although "unreasonable risk" is not defined in the Act, the House Report states:

> In general, a determination that a risk associated with a chemical substance or mixture is unreasonable involves balancing the probability that harm will occur and the magnitude and severity of that harm against the effect of proposed regulatory action on the availability to society of the benefits of the substances or mixture . . . .

H.R. REP. NO. 94-1341, 94th Cong., 2d Sess. 14 (1976). John Hills and Phillip Spector discuss and recommend steps toward an expected value approach. *See* Hills, *Legal Decisions and Opinions in Pollution Cases*, 10 ENVT'L SCI. & TECH. 234, 238 (1976); Spector, *Regulation of Pesticides by the Environmental Protection Agency*, 5 ECOLOGY L.Q. 233, 260 (1976).

The House Report's specification of unreasonable risk continues as follows:

> The balancing process described above does not require a formal benefit-cost analysis under which a monetary value is assigned to the risks associated with a substance and to the cost to society of proposed regulatory action on the availability of such benefits. Because a monetary value often cannot be assigned to a benefit or cost, such an analysis would not be very useful.

Id. at 14.

78. For example, the internal transfer of benefits tends to be associated with a sharply focused group of proponents of the environmental risk taking, while the external transfer of the potential costs, diffused both spatially and temporally, is associated with a broader but less focused group of opponents. This imbalance in interests, for and against, is likely to lead to an imbalance in decision making, even for an ostensibly neutral cost-benefit analysis, unless the imbalance in interests is recognized and offset by the design of the decision making institutions. *See* M. OLSON, THE LOGIC OF COLLECTIVE ACTION 23-52 (1964).

of information, and so on. For instance, when the potential adverse effects of an environmental risk are many times greater than the potential benefits, a proper standard of proof of danger under the expected cost minimization criterion may be that there is only "at least a reasonable doubt" that the adverse effect will occur, rather than requiring a greater probability, such as "more likely than not," that the effect will occur. Simple rules of thumb embodied in legal and regulatory institutions may come closer to expected cost minimization than elaborate attempts at quantification.[79]

In an expected value sense, the resources and interests going into a decision process are properly balanced when the rules and incentives are adjusted to minimize the costs of wrong decisions in the long run. This expected value point of view, applied to environmental risk, means that false positives must be tolerated as the price of controlling false negatives.[80]

79. In the absence of sufficient information to produce numerical estimates of the potential costs, benefits, and probabilities, formal benefit-risk or decision analysis is still often recommended as a structure of the important elements which will need to be balanced without full quantification. In the implementation of the Flammable Fabrics Act, 15 U.S.C. §§ 1191-1204 (1970), formal decision analysis was applied with the major purpose of making sure that no important aspects of the problem were neglected. Personal interview with Myron Tribus, Senior Vice President, Research and Engineering, Xerox Corporation's Information Technology Group (1976). However, there is no guarantee that decision analysis will not focus on what in hindsight are clearly the wrong aspects of the problem. In the case of Tris, the principal tradeoff considered was the balance between increased cost of the garment with increased amounts of retardant and increased likelihood that the flame retardant standard would be "subverted" by housewives making their own cheaper, nonretarded children's sleepwear. Tribus, *Decision Analysis Approach to Satisfying the Requirements of the Flammable Fabrics Act*, ASTM STANDARDIZATION NEWS, Feb., 1973, at 22, 27. At the time of implementation, the Mrak Commission had just reported on similar chemicals, finding several of them carcinogenic. But there had been no investigation of toxicity, either acute or chronic, for Tris or the other chemicals proposed as retardants. *See* U.S. DEP'T OF HEALTH, EDUCATION, AND WELFARE, REPORT OF THE SECRETARY'S COMMISSION OF PESTICIDES AND THEIR RELATIONSHIP TO ENVIRONMENTAL HEALTH (1969). Five years later, the question of toxicity arose quite outside the original decision framework and implementation of the Flammable Fabrics Act, which was administered first by the Department of Commerce and then by the Consumer Product Safety Commission, see note 72 *supra*. Through independent efforts it was learned that Tris kills goldfish at one part per million. After exposure to more than 40 million people—Tris not only made up more than ten percent of the weight of many pyjamas, but also was used for mattresses, drapes, and so on—the National Cancer Institute found the chemical to be one of the most potent carcinogens ever tested. For a single year's exposure to Tris, the National Cancer Institute estimate of excess cancer mortality is 15,000; Bruce Ames' estimate is substantially higher. *See* N. Kim Hooper & Bruce Ames, Letter to U.S. Consumer Product Safety Commission, March 21, 1977; Mintz, *U.S. Bans Sleepwear Treated with Tris*, The Washington Post, Apr. 8, 1977, at A1, A4. The Consumer Product Safety Commission estimated that about 300 children from age zero to six would be fatally burned by their sleepwear in the absence of retardants. It must also be asked whether children younger than a year (with presumably less than 50 fatal burns per year as they are less mobile than older children) should be exposed to other flame retardants, for which there is evidence of latent hazard. *Id.*

80. Paul Oreffice, President of Dow Chemical Company, criticized regulatory agencies for seeking a "zero-risk" society. Washington [D.C.] Star, Jan. 28, 1978, § C, at 6. Clearly, zero risk is unobtainable. While more conservative than the approach limiting false positives, the expected value approach only attempts to balance one risk against another.

Under an expected value approach, given the asymmetries in potential cost, we should

5. *Three Qualifications*

This Article has suggested that an approach of expected value can be used to define acceptable risk and that this approach is superior to either of the one-sided approaches, limiting false positives or limiting false negatives. But the characteristics of environmental risk require that the expected value approach be modified in three ways before it can yield a satisfactory definition of acceptable risk. These qualifications are more easily stated than implemented; they will require careful thought and debate before they can be built into decision processes in a satisfactory way.

The first modification is necessary because of social risk aversion. Individuals will not accept actuarially fair gambles when potentially large losses may result.[81] The characteristic of collective risk means that the potential adverse consequences of environmental risk cannot be spread to average out catastrophic costs, and consequently society itself is risk averse.[82] Although a risk may be acceptable using only the expected value approach, it may be unacceptable when social risk aversion is considered. This much is easily stated; the hard part is to uncover a social consensus on the appropriate amount of risk aversion and then to build this amount into the institutions which manage environmental risks.

A second modification is required as a consequence of irreversibility. The value and timing of information is related to the degree of irreversibility. If an environmental risk proves catastrophic, there is no choice for the future except to live with the irreversible consequence. However, if the decision is postponed, the choice remains open and decision makers can make use of subsequent information. Irreversible commitment in the present greatly reduces the value of information to be gained in the future. The greater the prospect of improved information, the more important it is not to foreclose a choice irreversibly in the present. Conversely, the greater the irreversibility, the greater is the value of postponement. This dependence between the value of information and the timing of an irreversible commitment is often left out of conventional cost-benefit analyses. Greater precaution results from taking this dependence into account.[83]

accept perhaps several false positives for each false negative. Although it may take years, if ever, before it is known whether a risk classified and treated as a positive is a false positive or a true positive, it is possible to survey past alarms and nonalarms to see if later evaluation found them more or less severe than at their first appraisal. Edward Lawless' preliminary work in this direction suggests that we may be accepting more false negatives than false positives, contrary to the expected value criterion. *See* E. Lawless, Technology and Social Shock (report for the National Science Foundation).

81. An actuarially fair gamble is one for which the expected value is zero. Most people, for example, would refuse a coin flip where they could gain $100,000 with probability 0.5 but could lose $100,000 with the same probability, simply because they cannot afford the potential loss, even though this is an actuarially fair gamble.

82. For collective, environmentally transferred risk, the assumptions of the Arrow-Lind theorem will not be met. *See* Fisher, ***Environmental Externalities and the Arrow-Lind Public Investment Theorem***, 63 AM. ECON. REV. 722 (1973).

The third modification is necessary due to latency and irreversibility. A conventional cost-benefit analysis based on expected cost minimization considers only the discounted sums of the costs associated with potentially wrong decisions. The characteristics of latency and irreversibility result in a separation of the benefits, enjoyed in the present, from the potential costs, borne in the future. Due to this separation, those who bear the costs often are not those who enjoy the benefits. For this reason, the equity of the distribution of costs and benefits is a fundamental consideration for environmental risk. Since those who bear the potential costs may not be alive at the time a decision is made to accept an environmental risk, the problem of intertemporal equity is further compounded by the problem of representation in a current decision.[84] Thus, the question of what is an intertemporally fair distribution of benefit and potential cost is especially difficult. Taking intertemporal equity into consideration yields a more precautionary treatment of environmental risk than would be the case if only the discounted sums of potential costs and benefits were considered.

Expected cost minimization and the three modifications appropriate to the special characteristics of environmental risk suggest a more precautionary management of environmental risk, and a lower level of acceptable risk, than is frequently suggested. How much more conservative, and how this conservatism could be built into our regulatory, legal, and economic institutions, remains a difficult and unresolved problem.

6. *Reactive Versus Anticipatory Institutions*

Whether the appropriate institutional response to a problem should be reactive or anticipatory depends on the nature of the problem. For classical pollution, reactive institutions may be satisfactory and perhaps even desirable; environmental risk requires anticipatory institutions.

In a detailed case study of the Los Angeles smog problem, Krier and Ursin describe the following highly reactive mode of institutional response.[85] In the thirty-five years since the smog problem emerged, control policy has been a policy of least steps, or least cost steps. As complaints rose in the early 1940s, the easiest remedies were applied first; for exam-

83. *See* Fisher & Krutilla, ***Valuing Long Run Ecological Consequences and Irreversibilities***, 1 J. ENVT'L ECON. & MANAGEMENT 96 (1974). ***See also*** Arrow & Fisher, ***Environmental Preservation, Uncertainty, and Irreversibility***, 88 Q.J. ECON. 312 (1974).

84. *See* William Thomas ***et al.***, ***Working Paper on Equity,*** in COMMITTEE ON PRINCIPLES OF DECISION MAKING FOR REGULATING CHEMICALS IN THE ENVIRONMENT, NATIONAL RESEARCH COUNCIL, NATIONAL ACADEMY OF SCIENCES, DECISION MAKING FOR REGULATING CHEMICALS IN THE ENVIRONMENT, app. E (1975). ***See also*** T. PAGE, CONSERVATION AND ECONOMIC EFFICIENCY 143-207 (1977).

85. J. KRIER & E. URSIN, POLLUTION AND POLICY: A CASE ESSAY ON CALIFORNIA AND FEDERAL EXPERIENCE WITH MOTOR VEHICLE AIR POLLUTION, 1940-1975, at 42-132 (1977).

ple, the temporary shutdown of a synthetic rubber plant with highly visible fumes was one of the first actions taken.[86] Control measures were adopted in response to specific crises and outcries of the public. Because the control measures were in response to immediate crises, the proposed solutions tended to be "immediate" as well. Control policy favored regulatory requirements and technological fixes, with existing or quickly developed technology (for example, requiring crankcase blow-by devices) over taxes and other economic incentives, which were perceived as slower and less certain. If one solution proved inadequate, there would be a lag, gradual realization of the inadequacy, perhaps another crisis, and then another incremental, least-cost solution proposed. Thus, it was only after more than twenty years of gradually eliminating more easily contained sources of air pollution that automobiles were discovered to be the principal source of Los Angeles smog; the other sources had been controlled, but the smog problem remained.[87]

For classical pollution this reactive policy can be viewed as largely self-correcting. It may be rational and workable under the criterion of expected cost minimization, as it guards against active policy mistakes and too abrupt and costly change. But for environmental risk the process of incremental reaction is not self-correcting. Because of latency, an effect is irreversibly determined before it is clearly observed. And because of the diffusion of the effect, and its hidden and probabilistic nature, the perception of crisis may itself be diffused, as has happened in the case of carcinogens in drinking water. Rather than relying upon crisis as the motive force in regulatory control, or upon the perception of past failures, adequate control of environmental risks requires institutions that anticipate the risks. Importantly, the same concept of expected cost minimization suggests that a reactive policy can be consistent with some kinds of classical pollution while wholly inadequate for environmental risk. Different types of problems should be treated differently, even under the same concept of rationality.

One of the main obstacles to satisfactory management of environmental risks is that concepts and institutions which developed in response to classical problems have been applied indiscriminately to environmental risks. For example, in opposing a ban on freon as a precaution against ozone depletion, a spokesman for E.I. du Pont deNemours & Co. argued: "No product should be banned on the basis of a scientific prediction of an adverse effect, but only on the basis of solid evidence that the damage is occurring."[88] This can be identified as the approach limiting false positives,

86. *Id.* at 53-54.

87. For a detailed description of the effort to discover and document the precise contribution of motor vehicles to Southern California's pollution conditions, see *id.* at 77-101.

88. Tannenbaum, *The Ozone Issue: Fluorocarbon Battle to Heat Up As the Regulators Move Beyond Aerosols*, The Wall St. J., Jan. 19, 1978, at 38, col. 2.

sometimes suitable for classical pollution, but not for ozone depletion, an important example of environmental risk.

Two recent cases illustrate increased judicial recognition of the need to respond to environmental risk problems in a precautionary and anticipatory manner. In *Reserve Mining Co. v. EPA*,[89] the Court of Appeals for the Eighth Circuit, in reviewing evidence on the potential carcinogenic effect of taconite tailings being discharged into Lake Superior, was unable to find that the "probability of harm [was] more likely than not."[90] The court nevertheless recognized that preventive judicial action was justified on the evidence of potential harm, although it modified the lower court's injunction to allow the company a "reasonable" time to abate the discharges.[91] In *Ethyl Corp. v. EPA*[92] the Court of Appeals for the District of Columbia upheld EPA's regulation of leaded gasoline based on the Administrator's determination that lead posed a "significant risk" to public health,[93] rejecting arguments that proof of either actual or even probable harm was necessary.[94] The court agreed with EPA that section 211 of the Clean Air Act,[95] which authorized regulation of gasoline additives whose emission products "will endanger" public health or welfare, was precautionary in nature.[96]

Similarly, recent federal legislation demonstrates growing congressional awareness of the need for a precautionary approach in the regulation of environmental risks.[97] For example, under the Toxic Substances Control Act,[98] the EPA Administrator is required to regulate a hazardous chemical substance or mixture upon a finding that it "presents or will present an unreasonable risk of injury to health or to the environment."[99]

89. 514 F.2d 492, 7 ERC 1618 (8th Cir. 1975).

90. *Id.* at 520, 7 ERC at 1636.

91. *Id.* at 535-40, 7 ERC at 1648-51.

92. 541 F.2d 1, 8 ERC 1785 (D.C. Cir. 1976).

93. *Id.* at 31-32, 8 ERC at 1807.

94. *Id.* at 13-20, 8 ERC at 1791-97. As support for its interpretation the court relied in part on *Reserve Mining*, stating that "*Reserve Mining* convincingly demonstrates that the magnitude of risk sufficient to justify regulation is inversely proportional to the harm to be avoided." *Id.* at 19, 8 ERC at 1797.

95. 42 U.S.C. § 1857f-6c(c)(1)(A) (1970) (prior to 1977 amendment).

96. 541 F.2d at 14, 8 ERC at 1795. The 1977 Amendments to the Clean Air Act amended § 211 in a manner which removes any doubt that the provision authorizes precautionary and anticipatory regulation. Section 211(c)(1)(A) now allows the Administrator to regulate fuel additives upon a determination that the additive "causes, or contributes to, air pollution which may reasonably be anticipated to endanger the public health or welfare . . . ." 42 U.S.C.A. § 7545(c)(1)(A) (West Supp. 1978).

97. *See generally* Doniger, *Federal Regulation of Vinyl Chloride: A Short Course in the Law and Policy of Toxic Substances Control*, 7 ECOLOGY L.Q. 497, 659-64 (1978).

98. 15 U.S.C.A. §§ 2601-2629 (West Supp. 1978).

99. *Id.* § 2605.

III
CONCLUSION

In summary:

(1) Toxic chemicals are one example of the more general class of problems labeled environmental risk.

(2) Environmental risk, though a very general type of problem, has nine defining characteristics.

(3) Environmental risk is not suited to management primarily on the basis of limiting false positives. Legal and regulatory methods that have been developed to manage classical pollution are inadequate for the management of environmental risks, because of the differences between the two types of problems.

(4) Limiting false negatives is more suited to environmental risk's characteristics than limiting false positives.

(5) A mixed approach, limiting both false positives and false negatives, through an expected value minimization, is more suited to environmental risk problems than either approach singly. Accommodating legal, regulatory, and economic institutions to the criterion of expected value minimization is made difficult by the modifications necessitated by risk aversion, irreversibility, and intertemporal equity. The criterion of expected value, suitably modified, is considerably more conservative than the current criterion limiting false positives.

(6) Incentives need to be restructured for institutions managing environmental risk so that they are less reactive and more anticipatory and precautionary.